

Production, Collection and Transport of Antiprotons: Optics improvements in P-bar transport lines

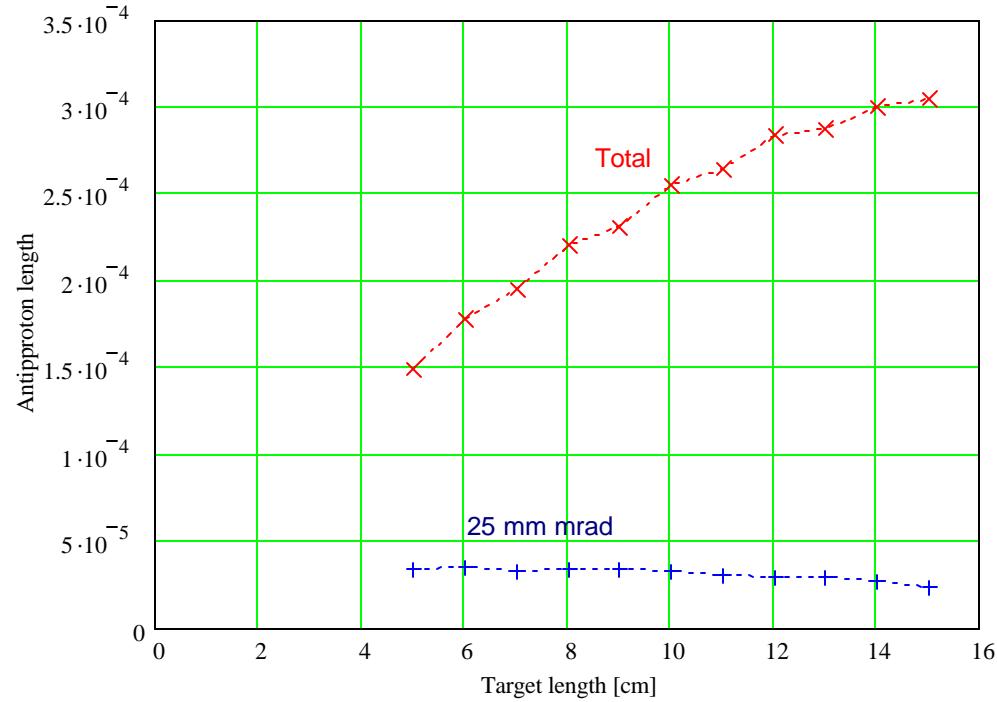
Valeri Lebedev

June 5, 2001

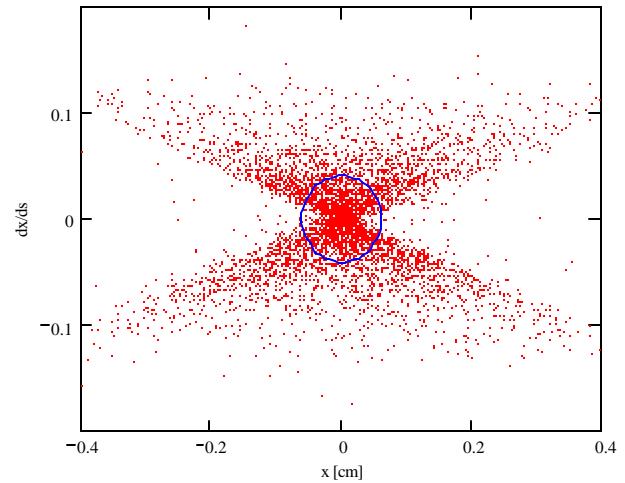
Talk outline

1. Antiproton yield from nickel target
2. Lithium lens and optimization of its focusing
 - Scattering and absorption of antiprotons
 - Linear focusing of the lens
 - Effect of lens non-linearities
 - Possible lens modifications
3. Antiproton transport in AP2 line
 - Optics improvements
 - Results of optics measurements
4. Optics improvements for AP1 and AP3 lines
5. Plans for future

Antiproton yield from nickel target

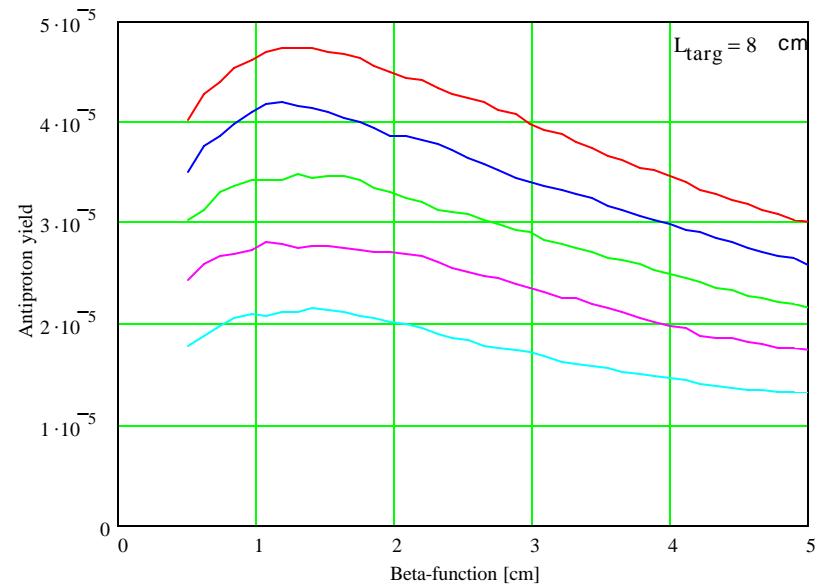
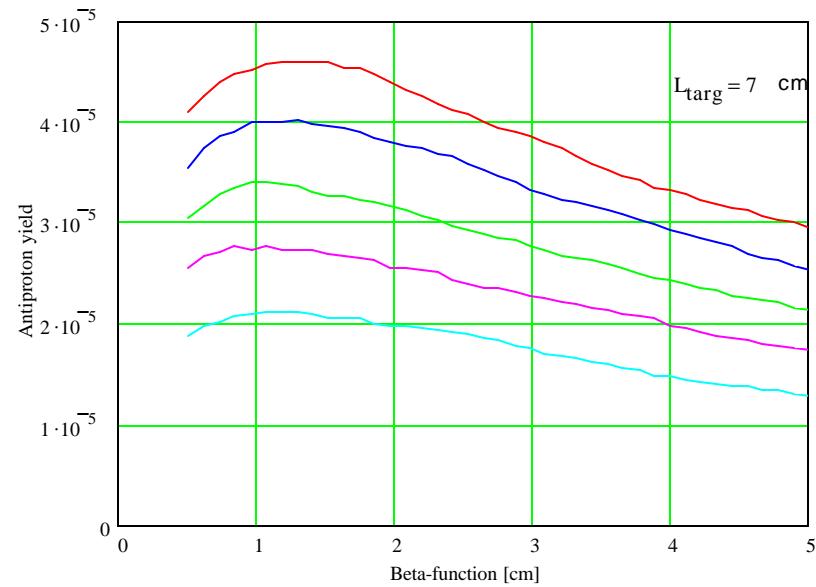
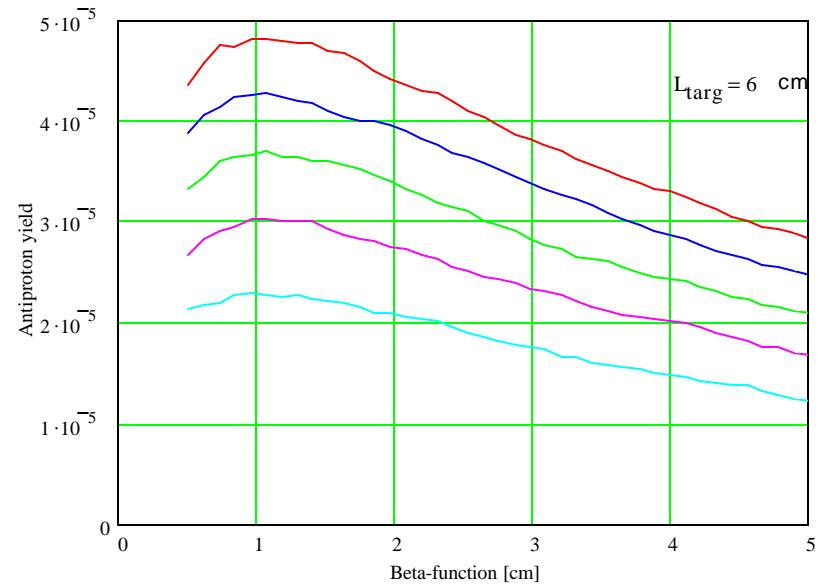
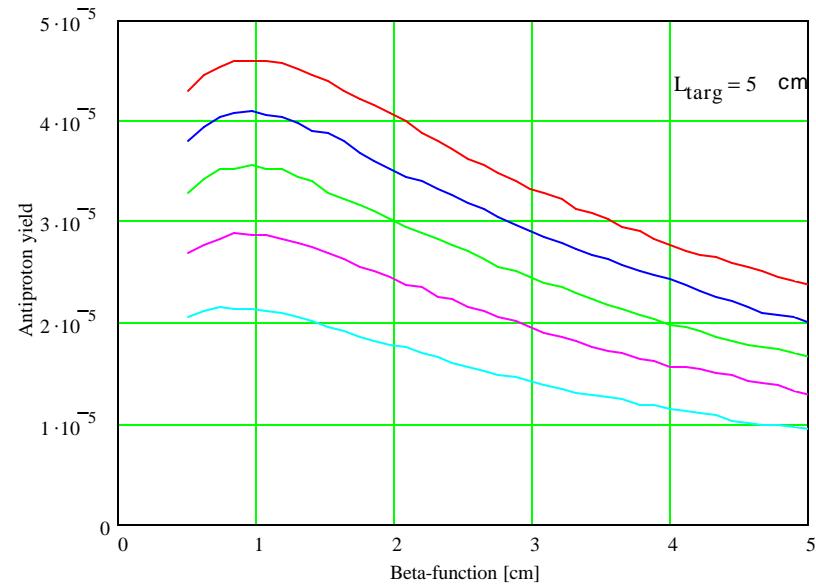


Total antiproton yield and optimized yield into 25 mm mrad as function of target length



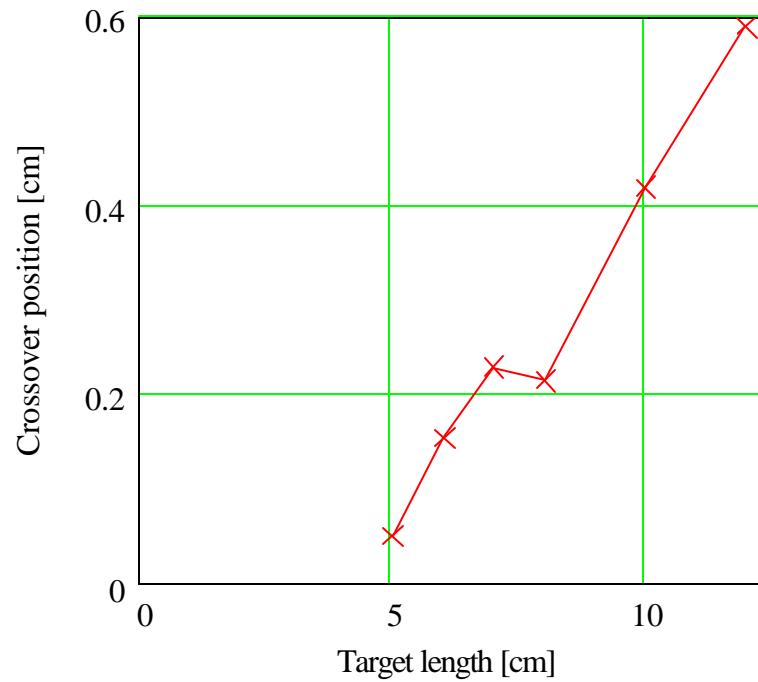
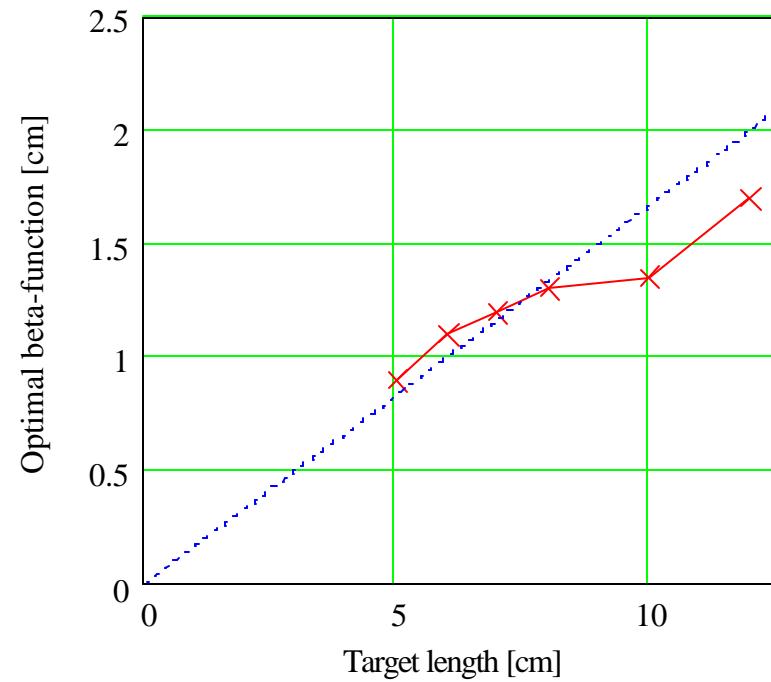
$$\left(\frac{x_i^2}{\mathbf{b}^*} + x_i'^2 \mathbf{b}^* \right) + \left(\frac{y_i^2}{\mathbf{b}^*} + y_i'^2 \mathbf{b}^* \right) \leq \mathbf{e}$$

$$\left| \frac{\Delta p_i}{p_0} \right| \leq 0.0225$$

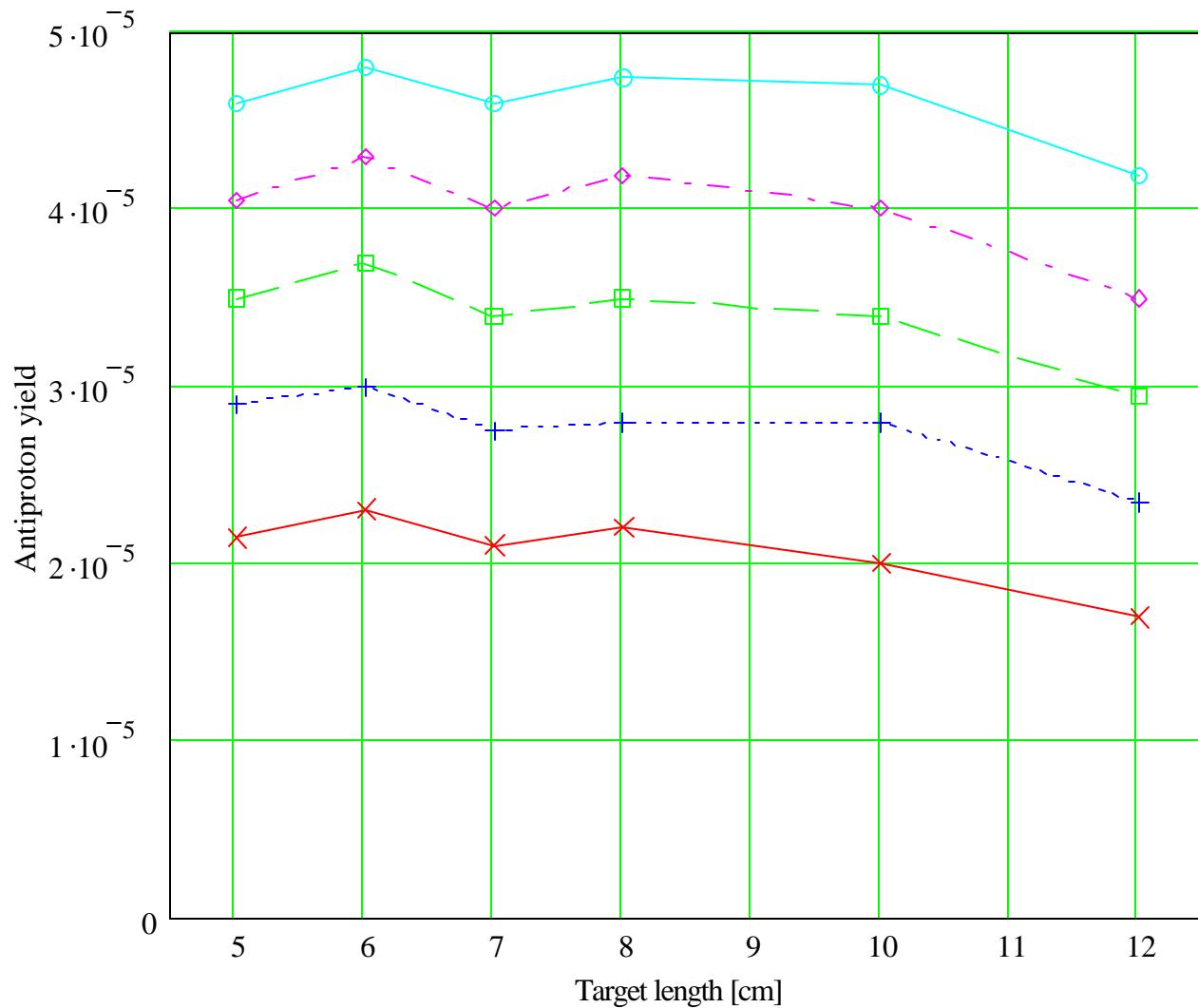


Antiproton yield into $\pm 2.25\%$ momentum spread and beam acceptances of 15, 20, 25, 30 and 35 mm mrad as function of the beta-function at the target and target length.

Rms beam size at the target is 100 μm



Dependence of optimal beta-function and crossover position on the target length.
Rms beam size at the target is 100 μm .



Dependence of maximum antiproton yield into $\pm 2.25\%$ momentum spread on the target length for the beam acceptances of 15, 20, 25, 30 and 35 mm mrad.
Rms beam size at the target is 100 μm .

Lithium lens and optimization of its focusing

Scattering and absorption of antiprotons in the lithium lens

- Nuclear scattering and absorption of antiprotons in the lithium lens is the major mechanism for antiproton loss in the lens

$$k_{lens} = \exp\left(-\frac{L_{Li}}{L_{Abs_{Li}}} - \frac{L_{Be}}{L_{Abs_{Be}}}\right) \approx 0.82 \text{ - for 15 cm lens}$$

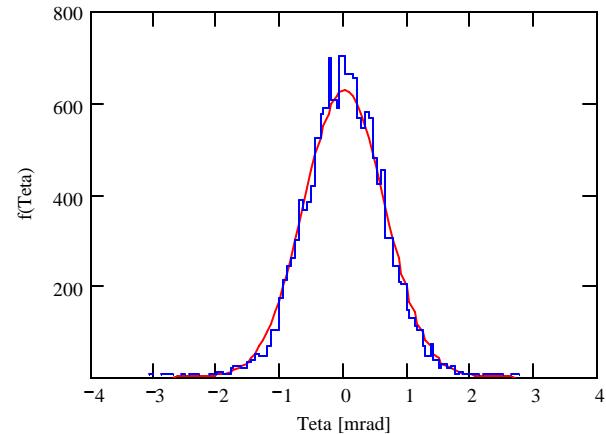
$L_{Li}=15.5$ cm and $L_{Be}=1.2$ cm are total lengths of lithium and beryllium

$L_{Abs_{Li}}=102$ cm and $L_{Abs_{Be}}=30.2$ cm are nuclear collision lengths for lithium and beryllium

- Multiple scattering in the lens can be estimated by the following formula,

$$\sqrt{\mathbf{q}^2} = \frac{13.6 \text{ MeV}}{\beta P c} \sqrt{\frac{L_{Li}}{X_{Li}} + \frac{L_{Be}}{X_{Be}}} \\ = 0.635 \text{ mrad ,}$$

$X_{Li}=155$ cm and $X_{Be}=35.3$ cm are the radiation lengths for lithium and beryllium

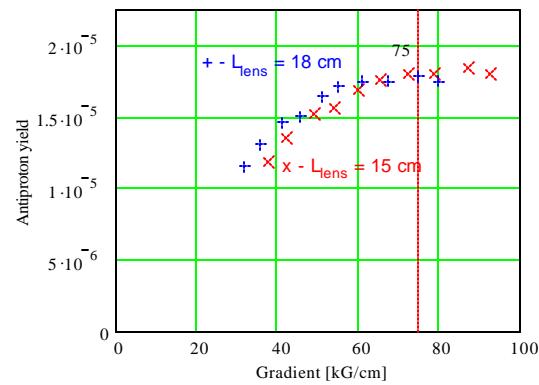


Distribution functions of point like beam after passing through lithium lens simulated by MARS and computed with use of multiple scattering formula

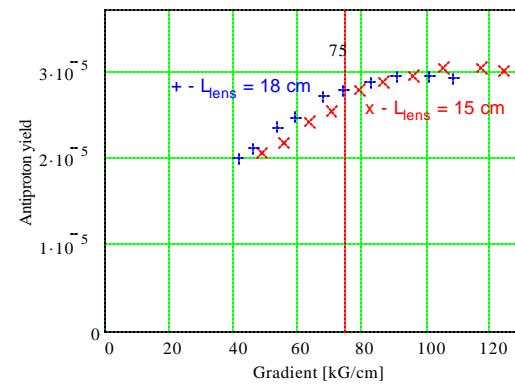
Linear focusing in the lens and its optimization

Optimization sequence

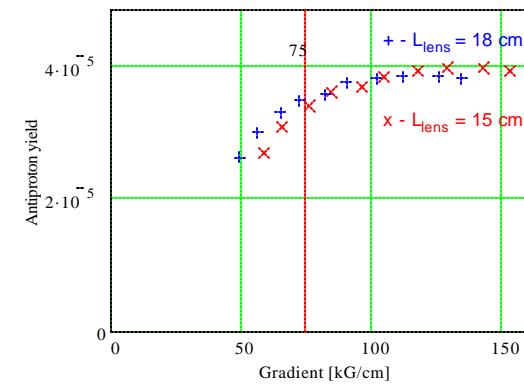
1. Chose acceptance
2. Chose beta-function on the target
3. Determine distance to the lens and lens focusing strength so that the beam size would be 1 cm (lens radius) and the beam size would be minimized in the first triplet
4. Chose optimized target length
5. Determine antiproton yield with lens absorption taken into account



15 mm mrad

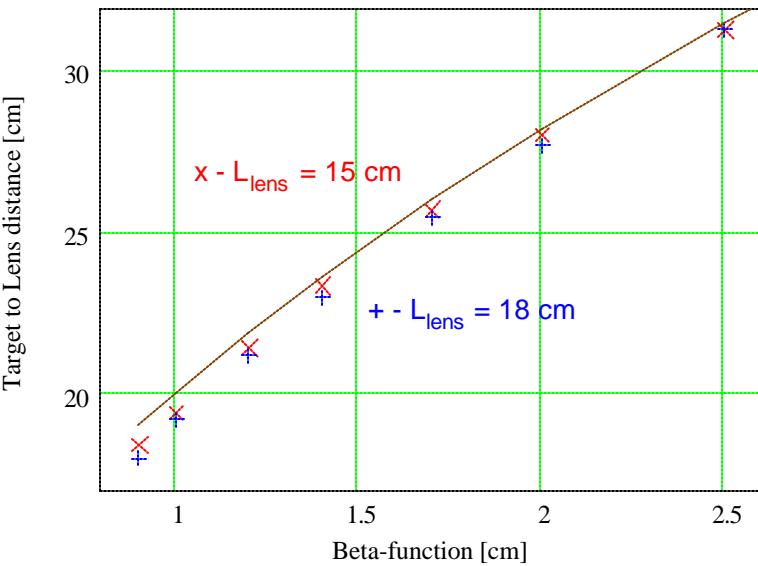
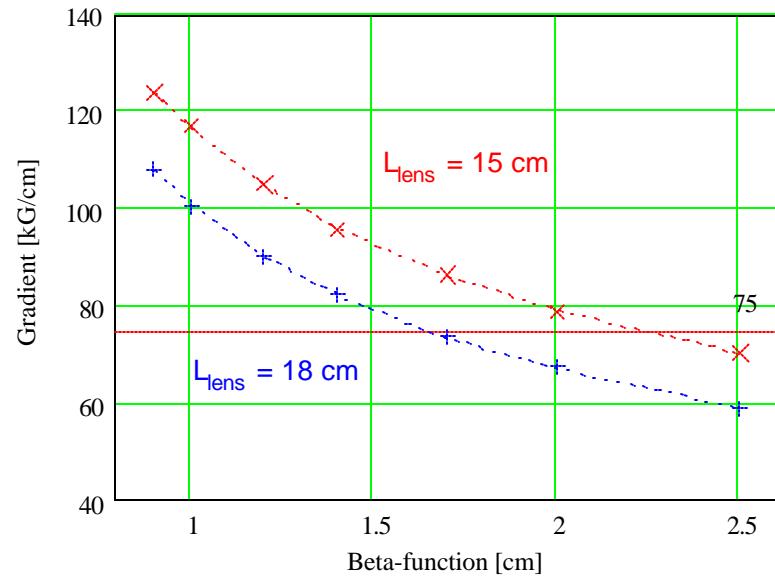


25 mm mrad



35 mm mrad

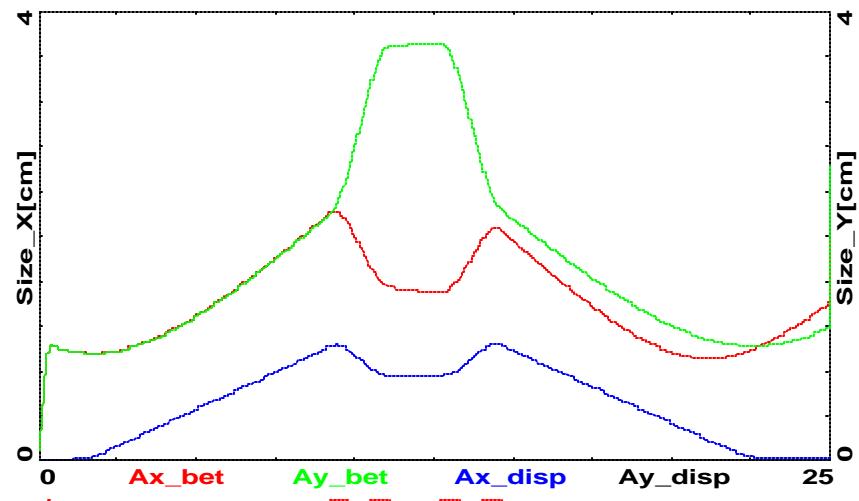
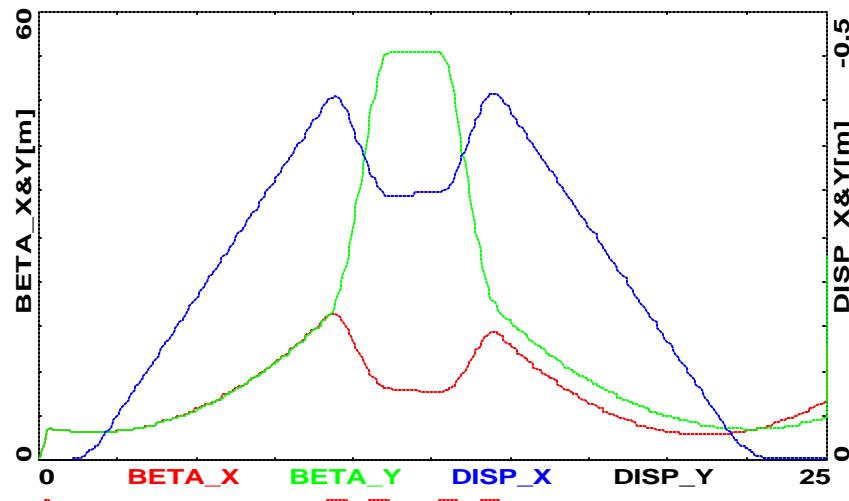
Dependence of optimized antiproton yield on lithium lens gradient. Absorption in the lens is taken into account



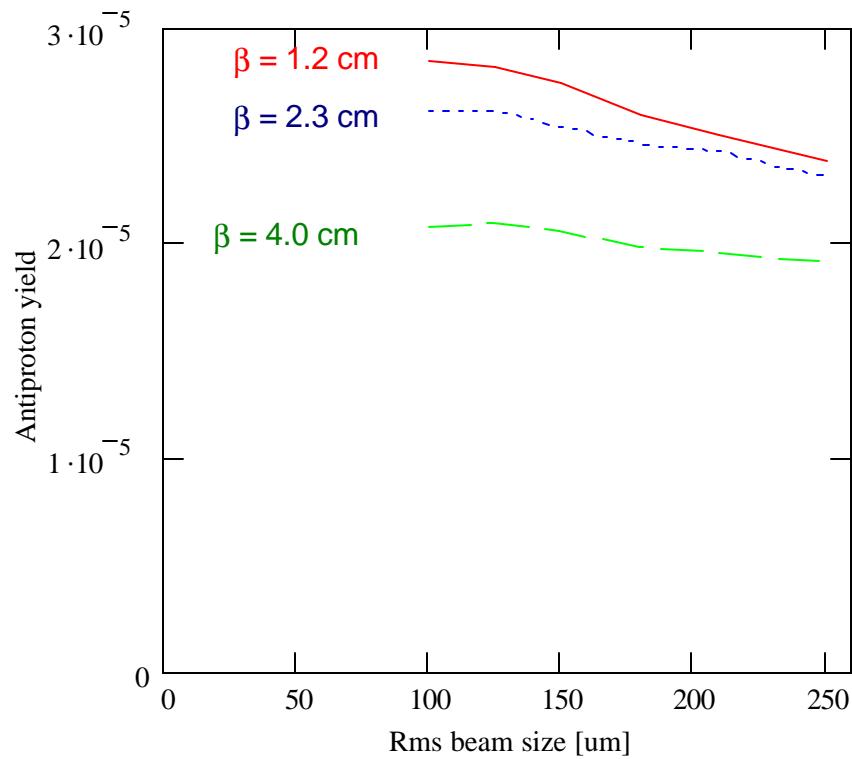
The lens gradient (left) and the center-to-center target-to-lens distance (right) $\epsilon = 25 \text{ mm}\cdot\text{mrad}$

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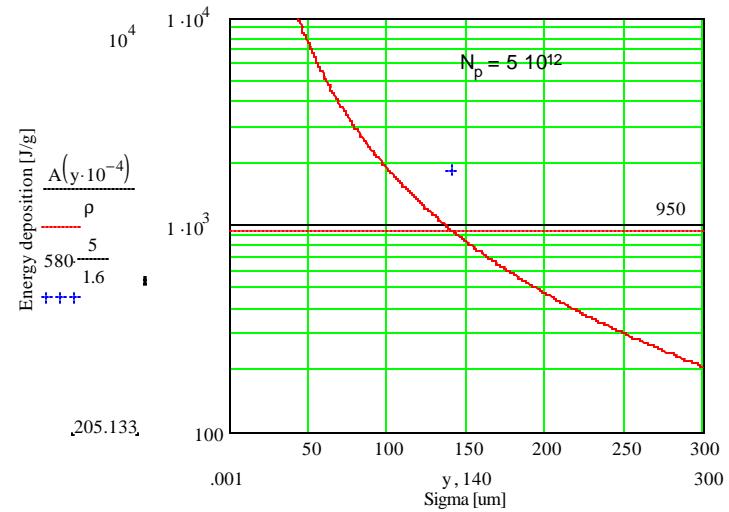
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Dispersion beta-functions (left) and beam envelopes (right) at the beginning of AP2 line
 $\epsilon = 25 \text{ mm}\cdot\text{mrad}$ and $b^* = 2.3 \text{ cm}$. Lithium lens gradient is 72 kG/cm.



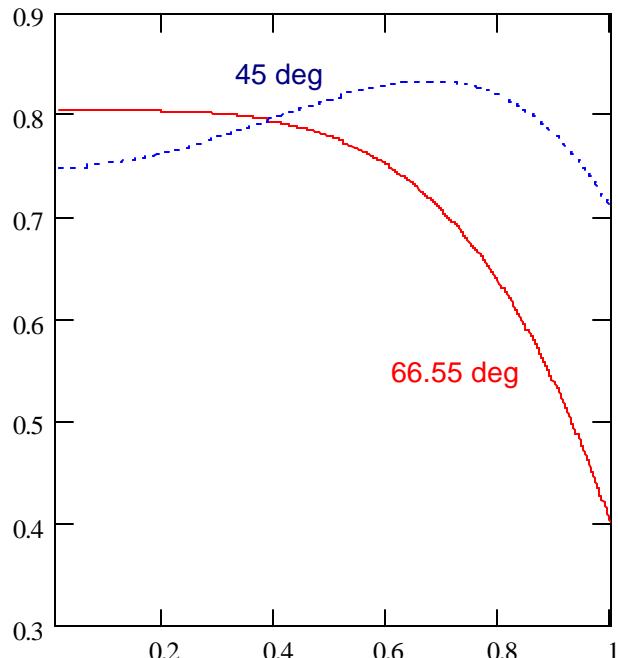
Dependence of antiproton yield on rms size of the proton beam
 acceptance of 25 mm mrad
 target length of 8 cm and
 Beta-function on the target: 1.2 cm – solid, 2.3 cm – dotted, and 4 cm – dashed curves



Dependence of energy deposition in the nickel target on the rms beam size for $5 \cdot 10^{-12}$ protons.
 Curve – ionization losses only
 Cross – total energy deposition

Non-linearity of lens focusing due to skin –effect

- 350 ms half period sinusoidal pulse
 - $\delta=0.5$ cm

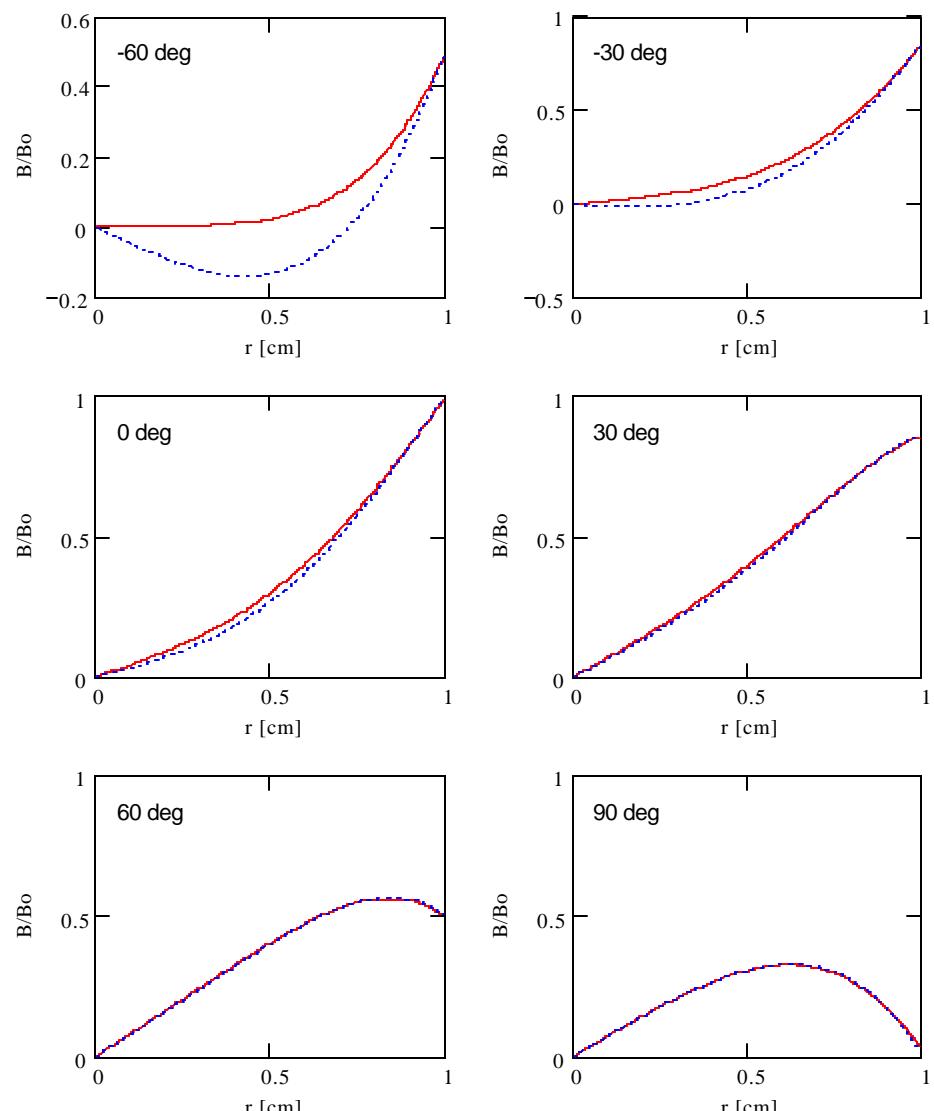


Dependence of focusing gradient on radius

Field calibration for 55 deg

$$B = \frac{2I_{lens}}{cR_{lens}} \cdot 0.948 \cdot 0.76$$

$$500 \text{ kA} - 72 \text{ kG/cm}$$



Dependence of magnetic field on radius

Effect of temperature gradient on lens nonlinearity

Steady state solution

$$T(r) = T(0) + \frac{P}{4\mathbf{p}k} \frac{r^2}{r_0^2} \Rightarrow \Delta T = 10 \text{ K} \Rightarrow \Delta j/j = 4\%$$

$$B(r) = B_0 \frac{r}{r_0} \left(1 + \frac{1}{2} \frac{\Delta j}{j} \frac{r^2}{r_0^2} \right) \Rightarrow \Delta B/B = 2\%$$

Relaxation time = 1.2 s versus repetition time = 1.5 s

Consideration of pulsed nature of lens heating exhibits significantly smaller result

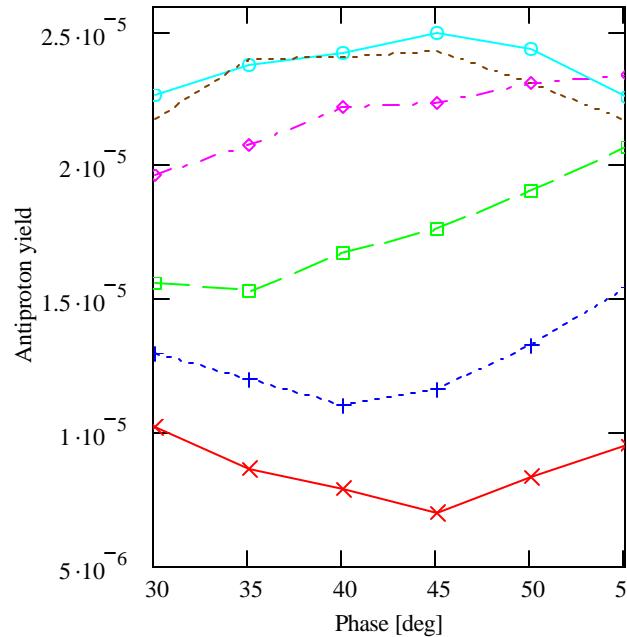
Effect of lens edges on lens nonlinearity

$$B_q(r, z) = \frac{2\mathbf{p}}{c} \left[r j_z(z) \Big|_{r=0} - \frac{r^3}{8} \frac{d^2}{dz^2} (j_z(z) \Big|_{r=0}) + \frac{r^5}{192} \frac{d^4}{dz^4} (j_z(z) \Big|_{r=0}) \right] + \dots$$

$$\frac{\Delta\Phi}{\Phi} = \frac{3}{8} \frac{rr'}{L_{lens}} \Rightarrow \Delta\Phi/\Phi \sim 10^{-3}$$

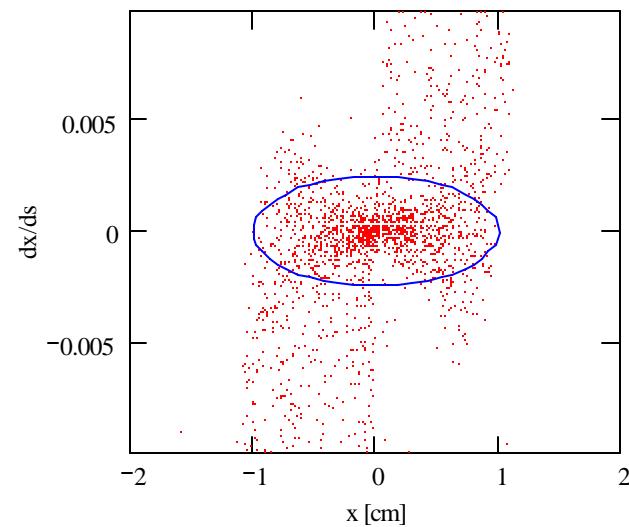
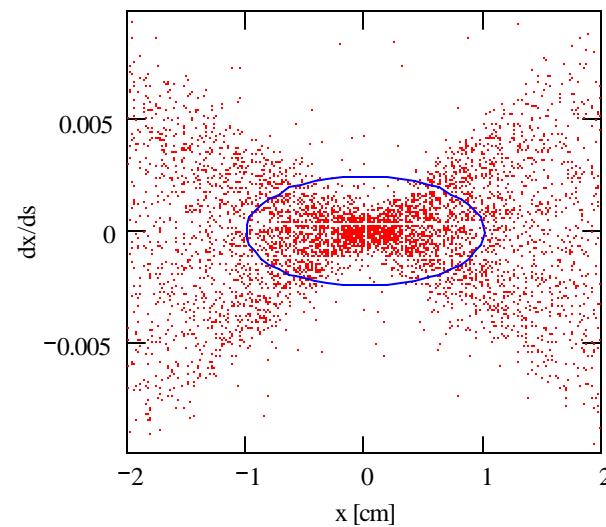
Effect of lens non-linearity and antiproton scattering on antiproton yield

particle



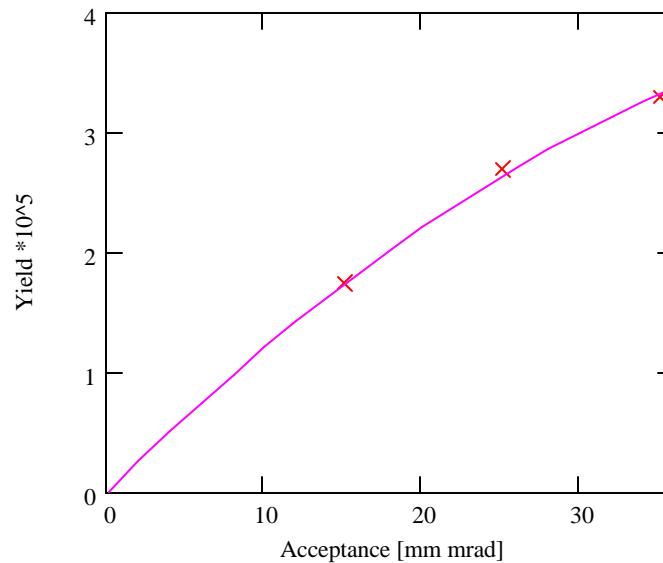
Antiproton yield

- Ideal lens $- k = 3.25 \cdot 10^{-5}$
- +Nuclear absorption - $k = 2.66 \cdot 10^{-5}$ (-18%)
- +Lens nonlinearity - $k = 2.70 \cdot 10^{-5}$ (+1.5%)
- +Multiple scattering - $k = 2.52 \cdot 10^{-5}$ (-6.5%)
- Emittance 25 mm marad
- Available accelerating gradient of the lens
- $b^* = 2.25$ cm
- $b_{\text{lens}} = 400$ cm
- lens to target length = 29.5 cm



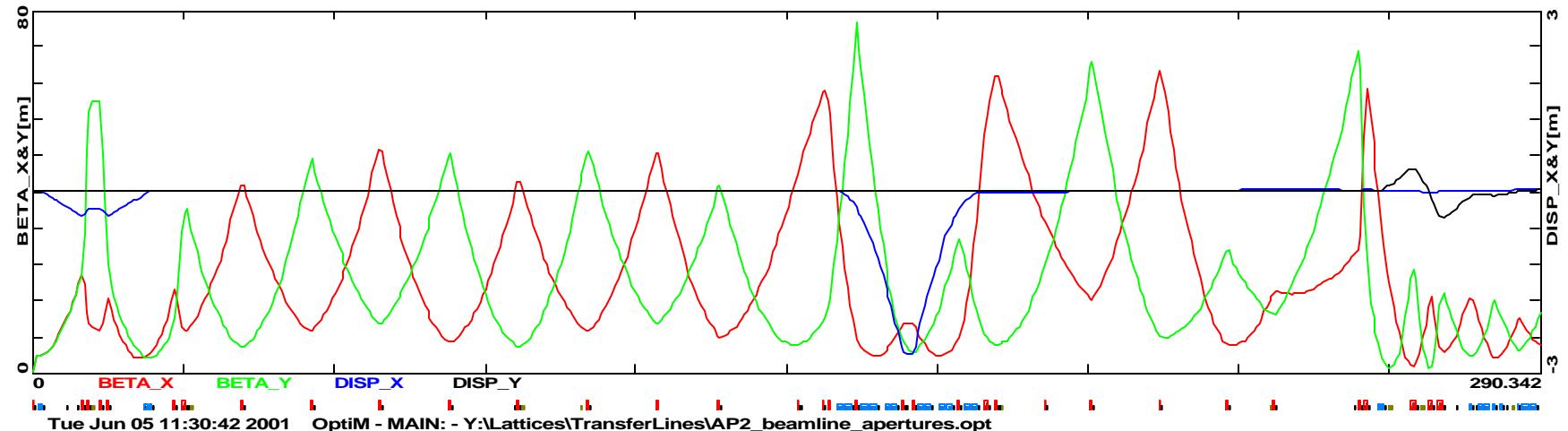
Possibilities to increase P-bar yield

1. 15 cm lens with unlimited current (liquid lithium etc.) – 10%
2. Longer lens (18 cm versus 15 cm) – 3%
3. Optics tuning – 50 to 100%
4. Acceptance increase

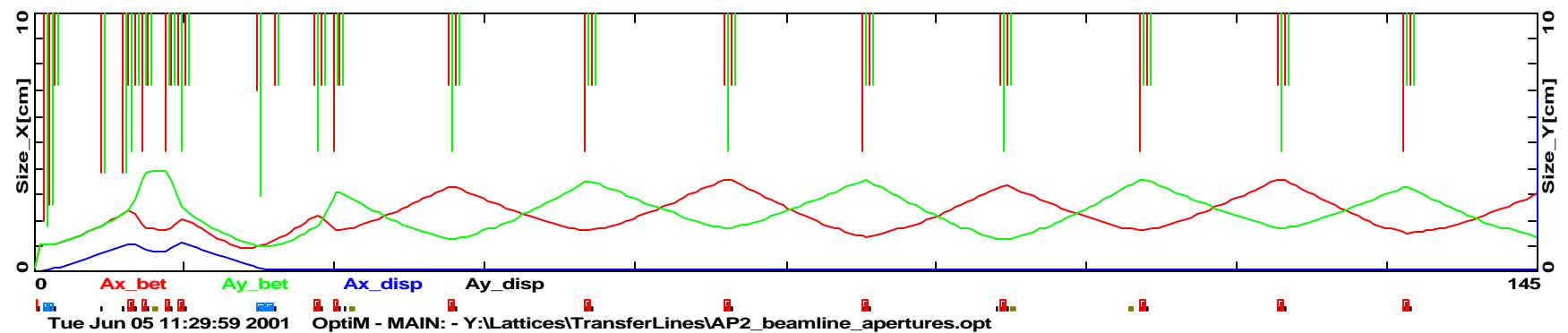


Antiproton transport in AP2 line

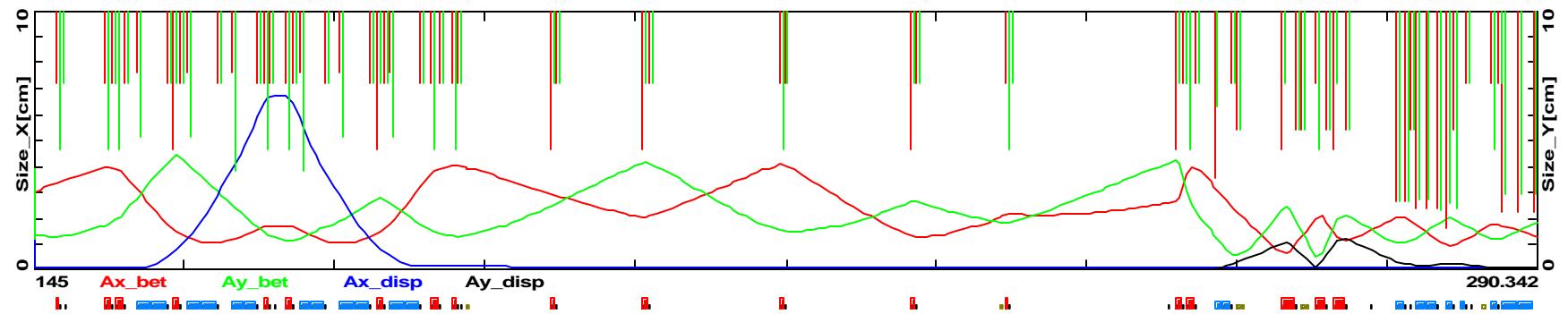
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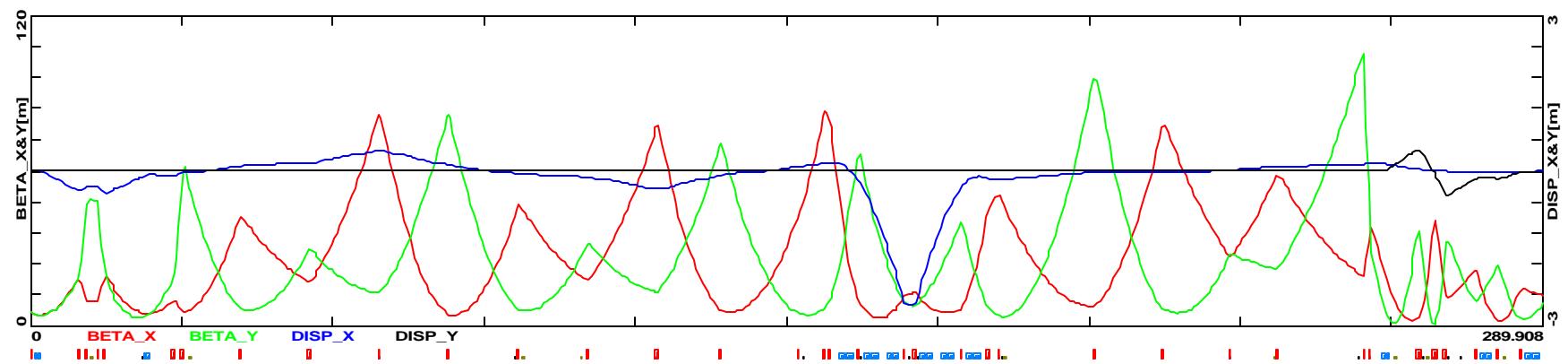


New optics features

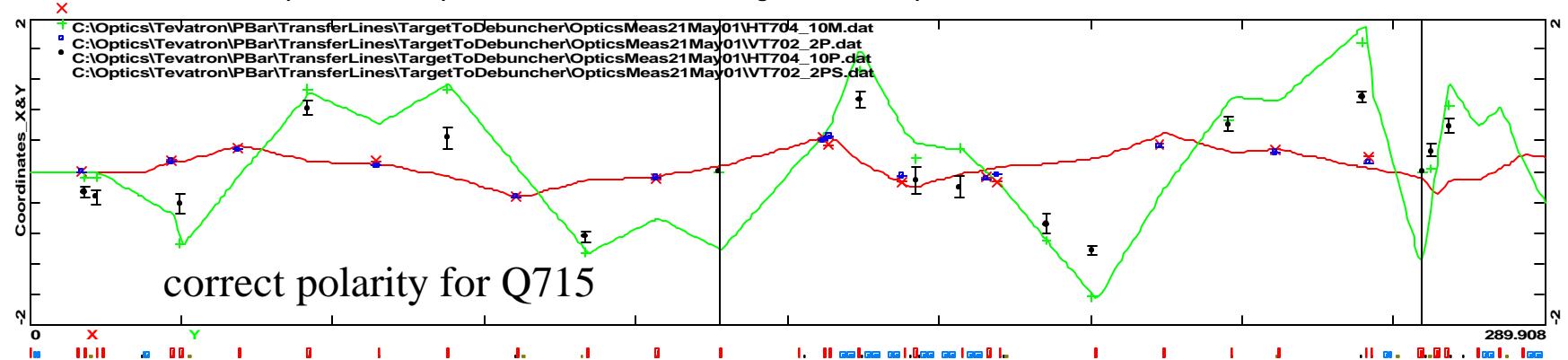
- Matched beta-functions and dispersions
We swapped two shunts – 20 to 60 A
Changed polarity for Q715
- Minimized beta-functions through the line
- Optics measurements and optics validation

Optics Measurements at May 21, 2001

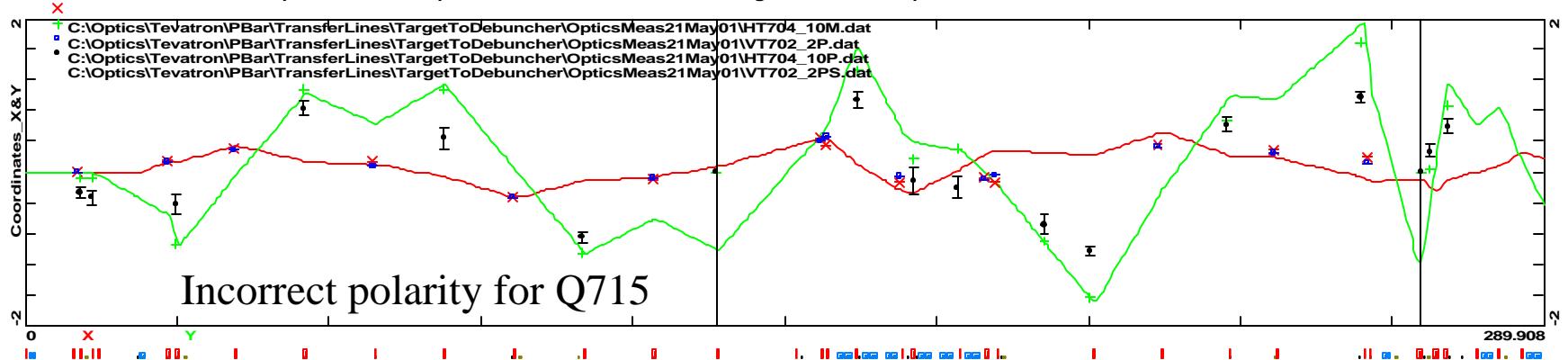
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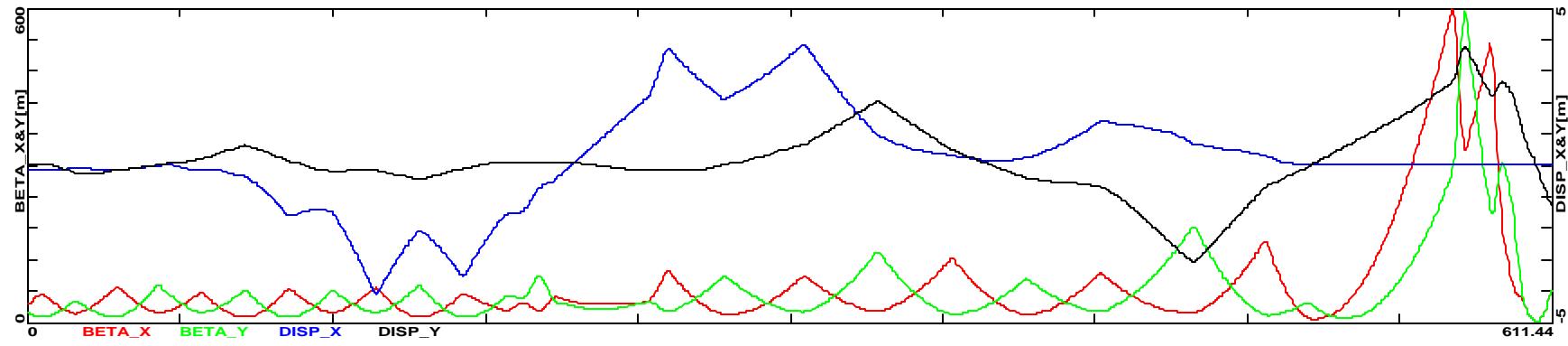


Plans for AP2 line studies

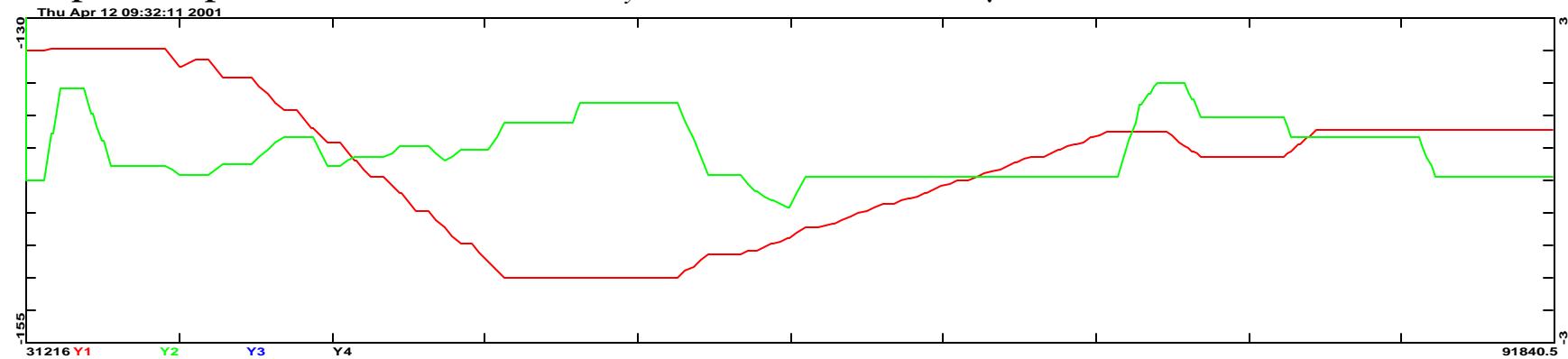
1. Optics measurements
 - Study of (1) reproducibility and (2) discrepancies in the optics
2. Calibration of lithium lens focusing
 - Measurement of antiproton yield as function of longitudinal target position
3. Tracking through the line with lithium lens taken into account
 - Do we need chromaticity correction
4. Study of pion propagation through the line

Main Injector to Target transport

- Desirable to have achromatic transport with the rms beam size at the target $< 100 - 150 \mu\text{m}$
 - $b^* < 50 \text{ cm}$
 - $D < 20 - 5 \text{ cm}$ for $\Delta p/p = (6-25) \cdot 10^{-4}$
- Currently we have $\sigma_x \approx 130 \mu\text{m}$, $\sigma_y \approx 220 \mu\text{m}$ with vertical beam size growing with beam momentum spread
- Recommendations for optics tuning

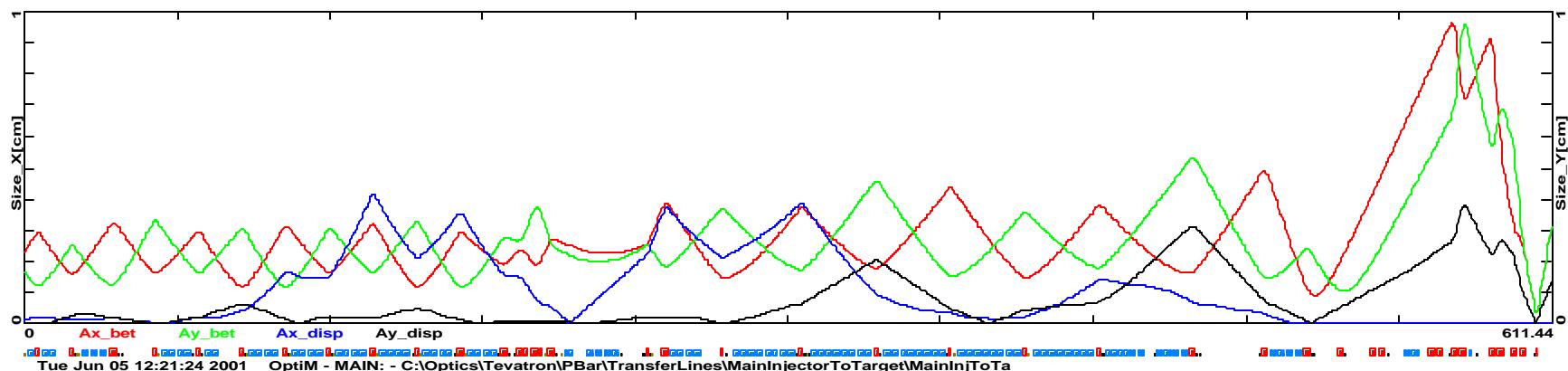


Proposed optics: $b^* = 68 \text{ cm}$, $D_x = D_y = 0$, $Dx' = 0$, $s = 130 \mu\text{m}$ for $e_n = 20 \text{ mm mrad}$

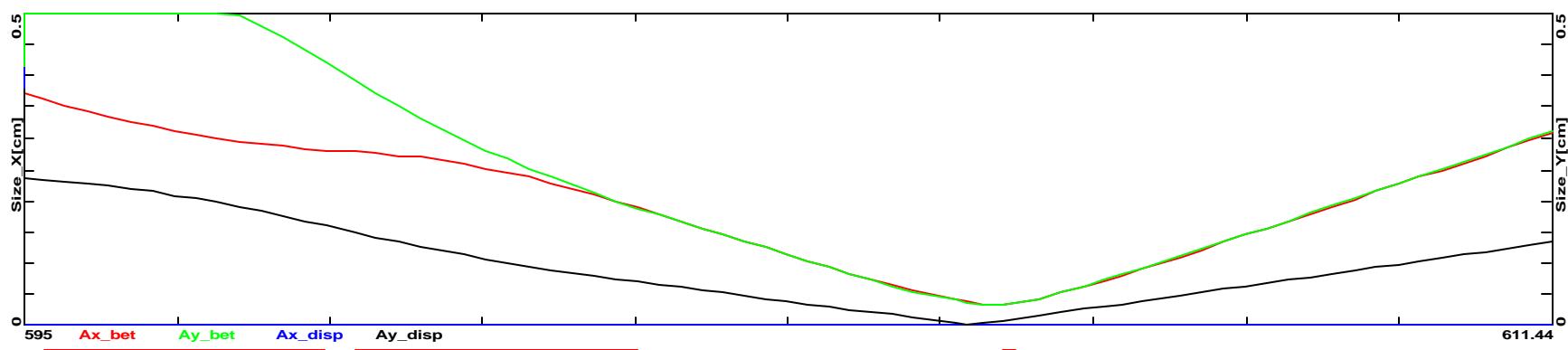


Impossible to zero vertical dispersion

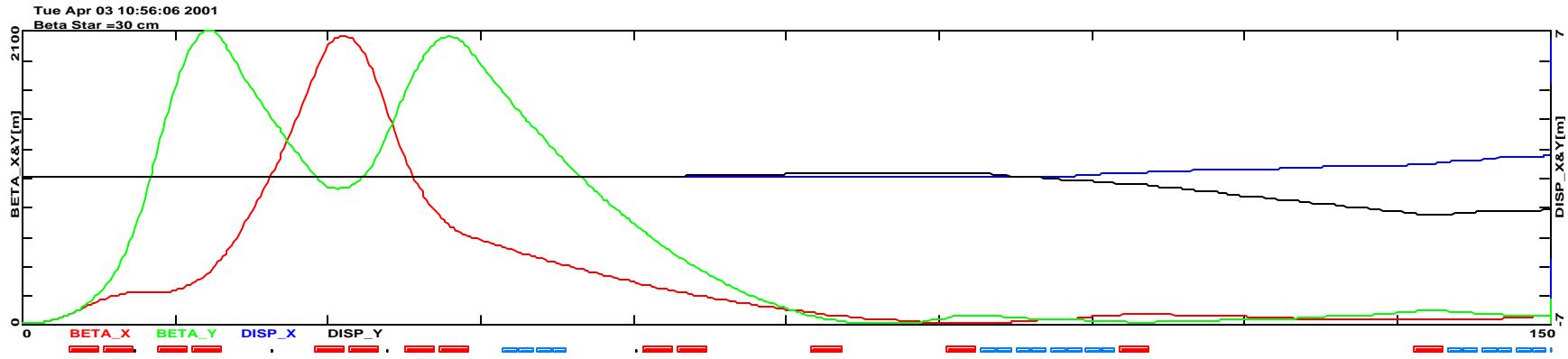
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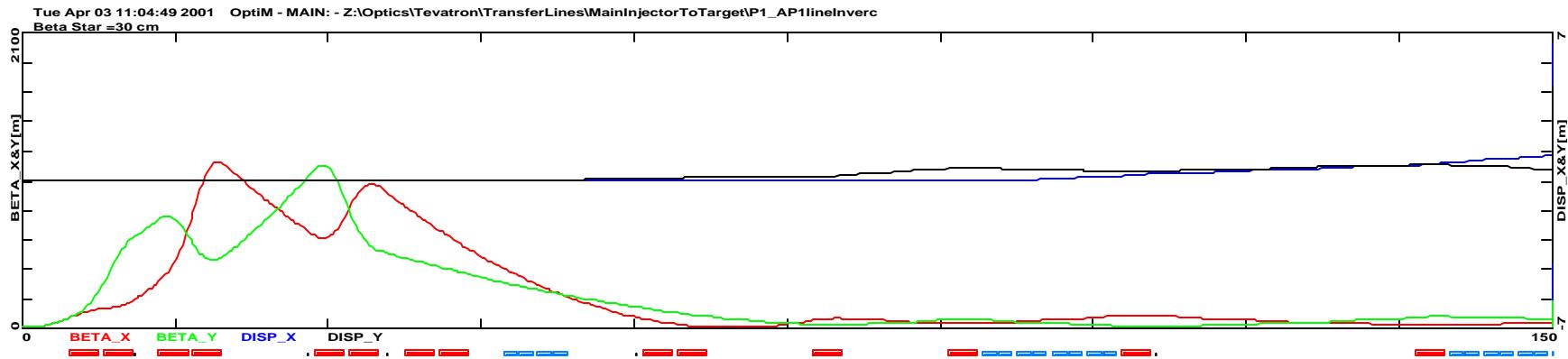
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Beam sizes for 95% normalized emittance of $20 \pi \text{ mm mrad}$ and $\Delta p/p = 10^{-3}$ ($s_p = 4 \cdot 10^{-4}$)
 $\sigma^* = 130 \mu\text{m}$



The best optics for current connection of quads, $G_{max}=0.93$ kG/cm; $B_{pole}=3.54$ kG, $I \approx 200$ A of 500 A



The best optics with reconnected quads, $G_{max}=2.2; 1.69; 1.69; 2.2$ kG/cm; $B_{pole}=8.38$ kG, $I \approx 470$ A of 500 A

Gradients and currents of quadrupoles for 120 GeV operation

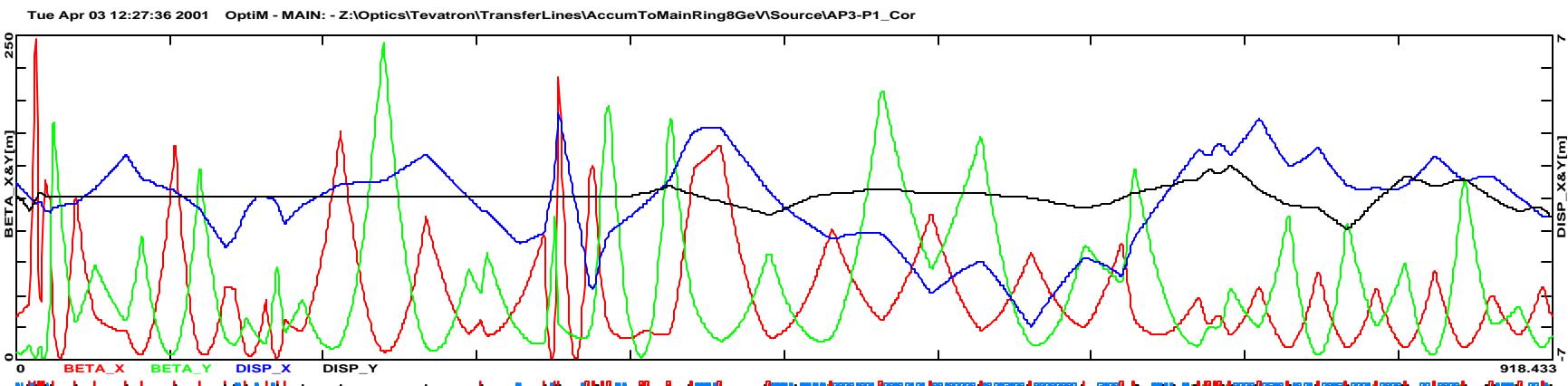
Power supply name	Power supply current [A]	Shunt name	Shunt current [A]	Quad name	Quad type	L[cm]	Aperture, 2a, [cm]	G[kG/cm]
				Q522		213.36		1.64076
P1 Line								
IQ701	259.9			Q701		304.8		-1.3041
IQ702	194.9			Q702		304.8		0.986002
IQ703	2593			Q703, Q705, Q707, Q709		213.36		-1.48547
				Q704, Q706, Q708		213.36		1.48547
IQ710	193			Q710		304.8		0.962833
IQ711	169			Q711		304.8		-0.84891
IQ712	162			Q712A		304.8		0.842468
				Q712B		152.4		0.837106
IQ713	252			Q713A		304.8		-1.27656
				Q713B		152.4		-1.26843
IQ714	236			Q714		304.8		1.16987
P2 Line								
IQF11A	365.2			QF11A		152.4		-1.74096
IQF11B	237.6			QF11B		304.8		1.17051
IQF12	1655.9			QF12, QF14, QF16 QF13, QF15, QF17		213.36 213.36		-0.94907 0.949072
AP1 line								
IQ201	162.4			Q201	3Q120	304.8	7.62	-0.74732
IQ202	217.5			Q202	3Q120	304.8	7.62	1.00094
IQ203	281.6			Q203	3Q120	304.8	7.62	-1.29605
IQ2071	308.3			Q2071	3Q120	304.8	7.62	1.41872
IQ2072	409.0			Q2072	3Q120	304.8	7.62	-1.88189
IQ208	478.1			Q1081, Q1092	3Q120	304.8	7.62	2.2
IQ209	365.1			Q1082, Q1091	3Q120	304.8	7.62	-1.68

Quads Q204, Q2061 and Q2062 have to be demagnetized and disconnected from power supplies.

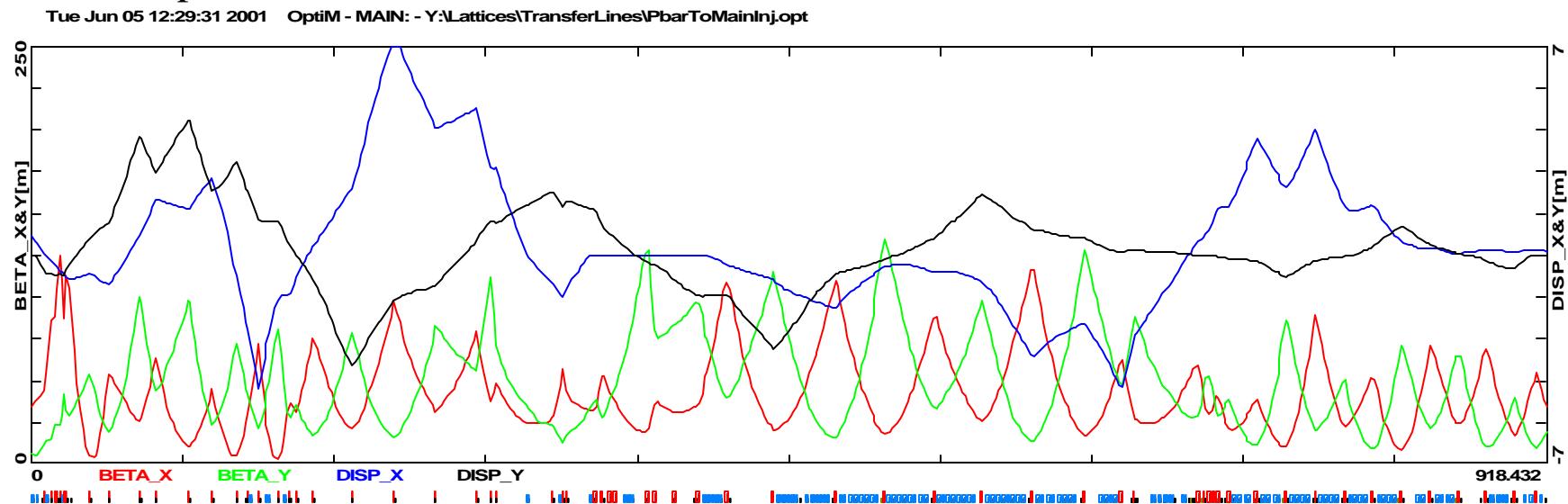
Quads Q2051 and Q2052 will be used for 8 GeV antiproton

PQ8A - PQ9B – have insufficient cooling and need to be swapped with other quads of AP1 line

Accumulator to Main Injector transport



Current optics



Proposed optics

Gradients and currents of quadrupoles for 8 GeV antiproton transport

Power supply name	Power supply current [A]	Shunt name	Shunt current [A]	Quad name	Quad Type	L[cm]	Aperture, 2a, [cm]	G[kG/cm]
AP3 line								
IQ901	104			Q901	SQC	70.1		-0.43142
IQ902	80			Q902	SQD	82.8		0.331517
IQ903	201.4			Q903A Q903B, Q906	SQD SQD	82.8 82.8		-0.83213 0.832134
				Q904	SQB	64.01		0
IQ905	252.2			Q905	SQC	70.1		-1.03996
IQ907	36.1			Q907	SQE	131.17		-0.15329
IQ908	179.1			Q908, Q912	SQA	45.72		0.74504
IQ909	114.7			Q909, Q913 Q916 Q918	SQA SQC SQA	45.72 70.1 45.72		-0.47679 -0.47577 -0.47679
IQ910	126.1			Q910 Q927	SQA SQC	45.72 70.1		0.52422 0.523138
IQ911	89.5			Q911, Q920	SQA	45.72		-0.37232
				Q914	SQA	45.72		0
IQ915	154.7			Q915	SQC	70.1		0.642237
IQ917	244.1			Q917	SQA	45.72		1.01184
IQ919	70.5			Q919 Q921	SQB SQA	64.01 45.72		0.293867 0.29404
IQ922	59			Q922 Q926 Q928	SQA SQB SQD	45.72 64.01 82.8		-0.24691 -0.24676 -0.24582
IQ923	98			Q923, Q925	SQA	45.72		0.407484
IQ924	165			Q924	SQA	45.72		-0.68636
AP1 line								
IQ2072	18.7			Q2072	3Q120	304.8		-0.09311
IQ2071	21.4			Q2071	3Q120	304.8		0.105616
				Q2062, Q2061	3Q120	304.8		0
IQ205	21.7			Q2052 Q2051	3Q120 3Q120	304.8 304.8		-0.10701 0.107006
				Q204	3Q120	304.8		0
IQ203	5.12			Q203	3Q120	304.8		-0.03025

IQ202	9.6			Q202	3Q120	304.8		0.050979
IQ201	7.21			Q201	3Q120	304.8		-0.03992
P2 line								
IQF12K	111			QF17		213.36		0.063616
				QF16		213.36		-0.06362
				QF15		213.36		0.063616
				QF14		213.36		-0.06362
				QF13		213.36		0.063616
				QF12		213.36		-0.06362
IQF11BK	17.01			QF11B		304.8		0.083825
IQF11AK	25.68			QF11A		152.4		-0.12241
P1 line								
IQ714K	18.47			Q714		304.8		0.091577
IQ713K	17.58			Q713B		152.4		-0.08849
				Q713A		304.8		-0.08906
IQ712K	13.11			Q712B		152.4		0.067741
				Q712A		304.8		0.068175
IQ711K	14.93			Q711		304.8		-0.07503
IQ710K	14.51			Q710		304.8		0.07239
IQ703K	187.55			Q709, Q707		213.36		-0.10745
				Q708, Q706		213.36		0.107445
				Q705, Q703		213.36		-0.10745
				Q704		213.36		0.107445
IQ702K	13.46			Q702		304.8		0.068074
IQ701K	19.63			Q701		304.8		-0.09851

- The same as for proton transport five quads of AP1 line (Q204, Q2061 and Q2062) have zero gradients and are not necessary for optics adjustments.
- Additionally, two quadrupoles of AP3 line (Q904 and Q914) are not required.
- All these quadrupoles have to be demagnetized and disconnected from power supplies. They can be dismounted later when new optics arrangement will prove that the beam transport is reliable and does not require further improvements

Conclusions, requests and questions

- Optics for both all P-bar lines needs to be improved
 - Reconnection of power supplies
 - Setting new focusing strength for quads
- Currently we have decent magnetic measurements for all quad types
 - 3Q120 were remeasured
 - Field maps were corrected
- Setting reliable hysteresis protocol
 - Has to be supported by control system
- Optics measurements and analysis
 - Fast and time effective measurements and on-line and off-line analysis
 - Effective online optics tuning??
- Bringing optics files in order
 - Positions of elements
 - Completeness of files
 - All elements related to optics (quads, correctors, BPMs, profile monitors) has to be in files
 - Consistency of different files